

February 2, 2008 7:25 WSPC/INSTRUCTION FILE meson-dsj

International Journal of Modern Physics A  
 © World Scientific Publishing Company

## Understanding open-charm mesons

J. Vijande<sup>1,2\*</sup>, F. Fernández<sup>1</sup>, A. Valcarce<sup>1</sup>.

<sup>1</sup>*Grupo de Física Nuclear and IUFFyM, Universidad de Salamanca, E-37008 Salamanca, Spain*

<sup>2</sup>*Dpto. de Física Teórica and IFIC, Universidad de Valencia - CSIC, E-46100 Burjassot, Valencia, Spain*

We present a theoretical framework that accounts for the new  $D_J$  and  $D_{sJ}$  mesons measured in the open-charm sector. These resonances are properly described if considered as a mixture of conventional  $P$ -wave quark-antiquark states and four-quark components. The narrowest states are basically  $P$ -wave quark-antiquark mesons, while the dominantly four-quark states are shifted above the corresponding two-meson threshold. We study the electromagnetic decay widths as basic tools to scrutiny their nature.

During the last few years, heavy meson spectroscopy is living a continuous excitation due to the discovery of several new charmed mesons. Three years ago BABAR Collaboration reported the observation of a charm-strange state, the  $D_{sJ}^*(2317)^1$ , that was later on confirmed by CLEO<sup>2</sup> and Belle Collaborations<sup>3</sup>. Besides, BABAR had also pointed out to the existence of another charm-strange meson, the  $D_{sJ}(2460)^1$ . This resonance was measured by CLEO<sup>2</sup> and confirmed by Belle<sup>3</sup>. Belle results are consistent with the assignments of  $J^P = 0^+$  for the  $D_{sJ}^*(2317)$  and  $J^P = 1^+$  for the  $D_{sJ}(2460)$ . However, although these states are well established, they present unexpected properties quite different from those predicted by quark potential models. If they would correspond to standard  $P$ -wave mesons made of a charm quark,  $c$ , and a strange antiquark,  $\bar{s}$ , their masses would be larger, around 2.48 GeV for the  $D_{sJ}^*(2317)$  and 2.55 GeV for the  $D_{sJ}(2460)$ . They would be therefore above the  $DK$  and  $D^*K$  thresholds, respectively, being broad resonances. However the states observed by BABAR and CLEO are very narrow,  $\Gamma < 4.6$  MeV for the  $D_{sJ}^*(2317)$  and  $\Gamma < 5.5$  MeV for the  $D_{sJ}(2460)$ .

The intriguing situation of the charm-strange mesons has been translated to the nonstrange sector with the Belle observation<sup>4</sup> of a nonstrange broad scalar resonance,  $D_0^*$ , with a mass of  $2308 \pm 17 \pm 15 \pm 28$  MeV/ $c^2$  and a width  $\Gamma = 276 \pm 21 \pm 18 \pm 60$  MeV. A state with similar properties has been suggested by FOCUS Collaboration at Fermilab<sup>5</sup> during the measurement of masses and widths of excited charm mesons  $D_2^*$ . This state generates for the open-charm nonstrange mesons a very similar problem to the one arising in the strange sector with the  $D_{sJ}^*(2317)$ . If the  $D_0^*(2308)$  would correspond to a standard  $P$ -wave meson made of a charm

\*E-mail address: javier.vijande@uv.es

Table 1.  $c\bar{s}$  and  $c\bar{n}$  masses (QM), in MeV. Experimental data (Exp.) are taken from Ref.<sup>9</sup>, except for the state denoted by a dagger that has been taken from Ref.<sup>4</sup>.

$nL J^P$	State	QM ( $c\bar{s}$ )	Exp.	State	QM ( $c\bar{n}$ )	Exp.
$1S 0^-$	$D_s$	1981	$1968.5 \pm 0.6$	$D$	1883	$1867.7 \pm 0.5$
$1S 1^-$	$D_s^*$	2112	$2112.4 \pm 0.7$	$D^*$	2010	$2008.9 \pm 0.5$
$1P 0^+$	$D_{sJ}^*(2317)$	2489	$2317.4 \pm 0.9$	$D_0^*(2308)$	2465	$2308 \pm 17 \pm 15 \pm 28^\dagger$
$1P 1^+$	$D_{sJ}(2460)$	2578	$2459.3 \pm 1.3$	$D_1(2420)$	2450	$2422.2 \pm 1.8$
$1P 1^+$	$D_{s1}(2536)$	2543	$2535.3 \pm 0.6$	$D_1^0(2430)$	2546	$2427 \pm 26 \pm 25$
$1P 2^+$	$D_{s2}(2573)$	2582	$2572.4 \pm 1.5$	$D_2^*(2460)$	2496	$2459 \pm 4$

quark,  $c$ , and a light antiquark,  $\bar{n}$ , its mass would have to be larger, around 2.46 GeV. In this case, the quark potential models prediction and the measured resonance are both above the  $D\pi$  threshold, the large width observed being expected although not its low mass.

The difficulties to identify the  $D_J$  and  $D_{sJ}$  states with conventional  $c\bar{n}$  mesons are rather similar to those appearing in the light-scalar meson sector<sup>6</sup> and may be indicating that other configurations are playing a role.  $q\bar{q}$  states are more easily identified with physical hadrons when virtual quark loops are not important. This is the case of the pseudoscalar and vector mesons, mainly due to the  $P$ -wave nature of this hadronic dressing. On the contrary, in the scalar sector is the  $q\bar{q}$  pair the one in a  $P$ -wave state, whereas quark loops may be in a  $S$ -wave. In this case the intermediate hadronic states that are created may play a crucial role in the composition of the resonance, in other words unquenching is important. This has been shown to be relevant for the proper description of the low-lying scalar mesons<sup>7</sup>.

In this work we have explored the same ideas for the understanding of the properties of the  $D_J$  and  $D_{sJ}$  meson states. In non-relativistic quark models the wave function of a zero baryon number ( $B=0$ ) hadron may be written as  $|B=0\rangle = \Omega_1 |q\bar{q}\rangle + \Omega_2 |qq\bar{q}\bar{q}\rangle + \dots$  where  $q$  stands for quark degrees of freedom and the coefficients  $\Omega_i$  take into account the mixing of four- and two-quark states. The hamiltonian considering the mixing between both configurations could be described using the  $^3P_0$  model, however, since this model depends on the vertex parameter, we prefer in a first approximation to parametrize this coefficient by looking to the quark pair that is annihilated and not to the spectator quarks that will form the final  $q\bar{q}$  state. Therefore we have taken  $V_{q\bar{q} \leftrightarrow qq\bar{q}\bar{q}} = \gamma$ . Further details about the formalism and the constituent quark model used are given in Refs.<sup>7,8</sup>.

A thoroughly study of the full meson spectra has been presented in Ref.<sup>8</sup>. The results for the open-charm mesons are resumed in Table 1. It can be seen how the open-charm states are easily identified with standard  $c\bar{n}$  mesons except for the cases of the  $D_{sJ}^*(2317)$ , the  $D_{sJ}(2460)$ , and the  $D_0^*(2308)$ . This is a common behavior of almost all quark potential model calculations<sup>10</sup>. In a similar manner, quenched lattice NRQCD predicts for the  $D_{sJ}^*(2317)$  a mass of 2.44 GeV<sup>11</sup>, while using relativistic charm quarks the mass obtained is 2.47 GeV<sup>12</sup>. Unquenched lattice QCD calculations of  $c\bar{s}$  states do not find a window for the  $D_{sJ}^*(2317)$ <sup>6</sup>, supporting the difficulty of a  $P$ -wave  $c\bar{s}$  interpretation.

Table 2. Probabilities (P), in %, of the wave function components and masses (QM), in MeV, of the open-charm mesons once the mixing between  $q\bar{q}$  and  $qq\bar{q}\bar{q}$  configurations is considered. Experimental data are taken from Ref.<sup>9</sup> except for the state denoted by a dagger that has been taken from Ref.<sup>4</sup>.

$I = 0$					$I = 1/2$	
$J^P = 0^+$		$J^P = 1^+$			$J^P = 0^+$	
QM	2339	QM	2421	2555	QM	2241
Exp.	2317.4±0.9	Exp.	2459.3±1.3	2535.3±0.6	Exp.	2308±17±15±28 <sup>†</sup>
P( $cn\bar{s}\bar{n}$ )	28	P( $cn\bar{s}\bar{n}$ )	25	~ 1	P( $cn\bar{n}\bar{n}$ )	46
P( $c\bar{s}_{13P}$ )	71	P( $c\bar{s}_{11P}$ )	74	~ 1	P( $c\bar{n}_{1P}$ )	53
P( $c\bar{s}_{23P}$ )	~ 1	P( $c\bar{s}_{13P}$ )	~ 1	98	P( $c\bar{n}_{2P}$ )	~ 1

Using for the  $qq$  interaction the parametrization of Ref.<sup>7</sup>, the results obtained for the  $cn\bar{s}\bar{n}$  configuration are 2731 and 2699 MeV for the  $J^P = 0^+$  with  $I = 0$  and  $I = 1$ , and 2841 and 2793 MeV for the  $J^P = 1^+$  with  $I = 0$  and  $I = 1$ . For the  $cn\bar{n}\bar{n}$  configuration with  $I = 1/2$  the energy is 2505 MeV. The  $I = 1$  and  $I = 0$  states are far above the corresponding strong decaying thresholds and therefore should be broad, what rules out a pure four-quark interpretation of the new open-charm mesons.

As outlined above, for  $P$ -wave mesons the hadronic dressing is in a  $S$ -wave, thus physical states may correspond to a mixing of two- and four-body configurations. In the isoscalar sector, the  $cn\bar{s}\bar{n}$  and  $c\bar{s}$  states get mixed, as it happens with  $cn\bar{n}\bar{n}$  and  $c\bar{n}$  for the  $I = 1/2$  case. The parameter  $\gamma$  has been fixed to reproduce the mass of the  $D_{sJ}^*(2317)$  meson,  $\gamma = 240$  MeV. The results obtained are shown in Table 2. Let us first analyze the nonstrange sector. The  $^3P_0$   $c\bar{n}$  pair and the  $cn\bar{n}\bar{n}$  have a mass of 2465 MeV and 2505 MeV, respectively. Once the mixing is considered one obtains a state at 2241 MeV with 46% of four-quark component and 53% of  $c\bar{n}$  pair. The lowest state, representing the  $D_0^*(2308)$ , is above the isospin preserving threshold  $D\pi$ , being broad as observed experimentally. The mixed configuration compares much better with the experimental data than the pure  $c\bar{n}$  state. The orthogonal state appears higher in energy, at 2713 MeV, with an important four-quark component.

Concerning the strange sector, the  $D_{sJ}^*(2317)$  and the  $D_{sJ}(2460)$  are dominantly  $c\bar{s}$   $J = 0^+$  and  $J = 1^+$  states, respectively, with almost 30% of four-quark component. Such component is responsible for the shift of the mass of the unmixed states to the experimental values below the  $DK$  and  $D^*K$  thresholds. Being both states below their isospin-preserving two-meson threshold, the only allowed strong decays to  $D_s^*\pi$  would violate isospin and are expected to have small widths  $O(10)$  keV<sup>13,14</sup>. As a consequence, they should be narrower than the  $D_{s2}(2573)$  and  $D_{s1}(2536)$ , opposite to what it is expected from heavy quark symmetry. The second isoscalar  $J^P = 1^+$  state, with an energy of 2555 MeV and 98% of  $c\bar{s}$  component, corresponds to the  $D_{s1}(2536)$ . Regarding the  $D_{sJ}^*(2317)$ , it has been argued that a possible  $DK$  molecule would be preferred with respect to an  $I = 0$   $cn\bar{s}\bar{n}$  tetraquark, what would anticipate an  $I = 1$   $cn\bar{s}\bar{n}$  partner nearby in mass<sup>15</sup>. Our results confirm the last argument, the vicinity of the isoscalar and isovector tetraquarks, however, the re-

Table 3. Electromagnetic decay widths, in keV, for the  $D_{sJ}^*(2317)$  and  $D_{sJ}(2460)$  (QM), compared to the results of two different quark models based only on  $q\bar{q}$  states. To compare with the experimental data by CLEO and Belle we have assumed for  $\Gamma(D_{sJ}^{*+}\pi^0) \approx \Gamma(D_{sJ}^+\pi^0) \approx 10$  keV as estimated in Ref. <sup>14</sup>.

Transition	Quark models			Experiments	
	QM	Ref. <sup>13</sup>	Ref. <sup>14</sup>	CLEO <sup>2</sup>	Belle <sup>3</sup>
$D_{sJ}^*(2317) \rightarrow D_s^{*+}\gamma$	1.6	1.74	1.9	$< 0.59$	$< 1.8$
$D_{sJ}(2460) \rightarrow D_s^{*+}\gamma$	0.06	4.66	5.5	$< 1.6$	$< 3.1$
$D_{sJ}(2460) \rightarrow D_s^+\gamma$	6.7	5.08	6.2	$< 4.9$	$5.5 \pm 1.3 \pm 0.8$

stricted coupling to the  $c\bar{s}$  system allowed only for the  $I = 0$  four-quark states opens the possibility of a mixed nature for the  $D_{sJ}^*(2317)$  while the  $I = 1$   $J = 0^+$  and  $J = 1^+$  four-quark states appear above 2700 MeV and cannot be shifted to lower energies.

Apart from the masses, the structure of the  $D_{sJ}^*(2317)$  and the  $D_{sJ}(2460)$  mesons could be scrutinied also through the study of their electromagnetic decay widths. We compare in Table 3 our results with different theoretical approaches and the experimental limits reported by Belle and CLEO. The main difference is noticed in the suppression predicted for the  $D_{sJ}(2460) \rightarrow D_s^{*+}\gamma$  decay as compared to the  $D_{sJ}(2460) \rightarrow D_s^+\gamma$ . A ratio  $D_{sJ}(2460) \rightarrow D_s^+\gamma / D_{sJ}(2460) \rightarrow D_s^{*+}\gamma \approx 1 - 2$  has been obtained assuming a  $q\bar{q}$  structure for both states<sup>13,14</sup> (what seems incompatible with their properties). We find a larger value,  $D_{sJ}(2460) \rightarrow D_s^+\gamma / D_{sJ}(2460) \rightarrow D_s^{*+}\gamma \approx 100$ , due to the small  $1^3P_1$   $c\bar{s}$  probability of the  $D_{sJ}(2460)$ . A similar enhancement has been obtained in Ref.<sup>16</sup> in the framework of light-cone QCD sum rules.

This work has been partially funded by Ministerio de Ciencia y Tecnología under Contract No. FPA2004-05616, by Junta de Castilla y León under Contract No. SA-104/04, and by Generalitat Valenciana under Contract No. GV05/276.

## References

1. B. Aubert *et al.*, [BABAR Collaboration], Phys. Rev. Lett. **90**, 242001 (2003).
2. D. Besson *et al.*, [CLEO Collaboration], Phys. Rev. D **68**, 032002 (2003).
3. Y. Mikani *et al.*, [Belle Collaboration], Phys. Rev. Lett. **92**, 012002 (2004).
4. K. Abe *et al.*, [Belle Collaboration], Phys. Rev. D **69**, 112002 (2004).
5. J.M. Link *et al.*, [FOCUS Collaboration], Phys. Lett. B **586**, 11 (2004).
6. G.S. Bali, Phys. Rev. D **68**, 071501(R) (2003).
7. J. Vijande *et al.*, Phys. Rev. D **72**, 034025 (2005).
8. J. Vijande, F. Fernández, and A. Valcarce, J. Phys. G **19**, 2013 (2005).
9. S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
10. S. Godfrey and R. Kokoski, Phys. Rev. D **43**, 1679 (1991).
11. J. Hein *et al.*, Phys. Rev. D **62**, 074503 (2000).
12. P. Boyle, [UKQCD Collaboration], Nucl. Phys. B (Proc. Supp.) **63**, 314 (1998).
13. W.A. Bardeen, E.J. Eichten, and C.T. Hill, Phys. Rev. D **68**, 054024 (2003).
14. S. Godfrey, Phys. Lett. B **568**, 254 (2003).
15. T. Barnes, F.E. Close, and H.J. Lipkin, Phys. Rev. D **68**, 054006 (2003).
16. P. Colangelo, F. de Fazio, and A. Ozzpineci, Phys. Rev. D **72**, 074004 (2005).